Geogr. Fis. Dinam. Quat.
19 (1996), 29-45, 14 figg., 2 tabb.

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PROPERTIES AND GEOGRAPHIC RELEVANCE OF FRAGIPAN AND OTHER CLOSE-PACKED HORIZONS IN A NON-GLACIATED MEDITERRANEAN REGION

ABSTRACT: COSTANTINI E.A.C. & NAPOLI R., *Properties and geographic relevance of fragipan and other close-packed horizons in a non-glaciated mediterranean region.* (IT ISSN 0391-9838, 1996).

To investigate the properties of different close-packed horizons present in soils evolved from mainly siliceous colluvia and alluvia in a Mediterranean environment several profiles were selected and analysed. Selection of the profiles occurred after a geomorphological and soil survey in an area known as «Montagnola Senese» in central Tuscany.

Close-packed horizons were classed according to their morphology as: (i) fragipan, (ii) glossic horizon, (iii) densipan and (iv) pedal dense subsurface horizon; they all showed the following properties: high bulk and packing density, very low hydraulic conductivity of the matrix and a porosity dominated by micropores. They all were free of carbonates and extracted silica did not occur in significant quantities. The great abundance of silt and very fine sand, derived from the alteration of schist and quartzite present in the parent material, was the main common characteristic of all close-packed horizons, although densipan and pedal dense subsurface horizon could be more clayey.

Geomorphological evidences showed that the area was undergone, since the late Pliocene, through several uplifting episodes that have resulted in slope erosion, colluviation and formation of extensive and thick deposits, followed by the draining of the saturated material. The origin of the high density of the examined horizons could be related to this particular geomorphological evolution of the surfaces during the Pleistocene, as well as to the lithology of the materials, having a high degree of sorting in the fine-earth fraction.

Differences in morphology between fragipan, densipan and glossic close-packed horizon call for distinct stages of a disintegration process, depending on the tree root penetration into the firm soil mass and on the distance between the close-packed horizon and the surface. The noticing of their position in the profile can allow the acquisition of useful information about the Quaternary geomorphological evolution of the areas where soils with this kind of close-packed horizon are present.

KEY-WORDS: Fragipan, Montagnola Senese, Mediterranean region, Italy.

RIASSUNTO: COSTANTINI E.A.C. & NAPOLI R., *Proprietà e importanza geografica dei fragipan e di altri orizzonti compatti in una regione mediterranea non interessata da processi glaciali.* (IT ISSN 0391-9838, 1996).

Sono state studiate le proprietà degli orizzonti compatti di alcuni suoli evolutisi sui depositi colluviali e alluvionali a matrice principalmente silicea di un ambiente Mediterraneo. Sulla base di un rilevamento pedologico e geomorfologico sono stati scelti e sottoposti ad analisi alcuni suoli rappresentativi. Le determinazioni sono state effettuate sugli interi orizzonti o su parti di essi (zone ossidate e zone ridotte) ed hanno previsto, oltre a quelle di routine, l'analisi della CSC dell'argilla, delle forme del ferro, del contenuto in silice, della porosità, della conducibilità idraulica e della micromorfologia in sezione sottile.

Gli orizzonti compatti sono stati distinti, secondo la loro morfologia, in: (1) fragipan, (2) orizzonti glossici, (3) densipan, (4) orizzonti di profondità densi e strutturati. Tutti i diversi orizzonti compatti sono stati rilevati in suoli su colluvioni e alluvioni prevalentemente silicee; mostrano evidenze di pedogenesi, hanno una elevata densità apparente ed addensamento delle particelle, conducibilità idraulica della matrice molto bassa e una porosità dominata dai micropori. I suoli sono privi di carbonati e la silice libera non è presente in quantità elevate. Una grande abbondanza di limo e sabbia molto fine, derivante dall'alterazione dello scisto e della quarzite presenti nel materiale d'origine, è caratteristica comune a tutti gli orizzonti compatti, ma nel caso dei densipan e degli orizzonti di profondità densi e strutturati la tessitura può essere più argillosa.

Le evidenze geomorfologiche mostrano che l'area in studio è stata interessata, sin dalla fine del Pliocene, da numerose fasi di sollevamento, con ripetuti fenomeni di erosione dei versanti e colluvionamento. Questi hanno condotto alla formazione di estesi e potenti depositi colluviali ed alluvionali che, in seguito all'abbassarsi del livello della falda idrica, hanno subito un processo di drenaggio. L'origine dell'elevata densità degli orizzonti esaminati può essere ricondotta proprio a questo tipo di evoluzione geomorfologica delle superfici durante il Quaternario, nonchè alla litologia dei materiali, caratterizzati da una elevata classazione delle particelle nella terra fine.

Le differenze morfologiche tra fragipan, densipan e orizzonti glossici compatti rappresentano diversi stadi di un processo di disgragazione causato dalla penetrazione delle radici delle piante arboree nella massa compatta del suolo e dalla distanza tra l'orizzonte consolidato e la superficie. L'esame della loro posizione nel profilo può permettere di ricavare informazioni utili per la ricostruzione della evoluzione geomorfologica nel corso del Quaternario delle aree dove sono presenti suoli con questo tipo di orizzonti compatti.

TERMINI CHIAVE: Fragipan, Montagnola Senese, Regione Mediterranea, Italia.

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Authors thank prof. F. Ugolini of the University of Florence for his helpful criticisms on style and content of the manuscript.

The work was carried out on an equal basis by the first two authors; dr. G. Bragato carried out physic-hydrological analysis and elaboration of the data. The authors acknowledge dr. A. Calì and Mrs. S. Simoncini for their great help in performing laboratory analysis.

1. INTRODUCTION

Many studies have been conducted in several parts of the world to decipher the origin and evolution of fragipan. In most of them, the genesis of fragipan has been associated with periglacial environment, such as the presence of permafrost (VAN VLIET-LANOË & LANGOHR, 1981, VAN VLIET-LANOË & *alii*, 1992), but fragipan formation has also been attributed to interaction between desiccation cycles and precipitation of SiO_2-rich amorphous aluminosilicate (HABECKER & *alii*, 1990), or to an increase of free iron oxides and silica, the latter generally > 0.2% (HARLAN & *alii*, 1977).

Besides periglacial and chemical processes, the genesis of fragipan has been related to physical ripening, i.e. dewatering of an initially slurried material (BRYANT, 1989). According to this hypothesis, the processes of rapid draining of lacustrine deposits, saturated colluvial deposits, depositions of wet glacial till and solifluction materials, imposed on materials displaying suitable physical characteristics, lead to the self- collapse of the sediments and to the fragipan formation. As reported by JHA and CLINE (1963), for soils of a lacustrine site of the N.E. United States, compaction by glacial ice, periglacial phenomena, or weight of overburdens, is not essential for development of density and firmness in fragipan. Finally, the low permeability of the underlying rock seems to play an important role in the formation of this horizon (BRUCKERT & BEKKARY, 1992). Whatever it might be is origin, fragipan is characterised by a preferred arrangement of grains in the matrix and a homogeneous textural class of parent material (LINDBO & VENEMAN, 1989), while high carbonate and a clay content of more than 35% are believed to be inhibiting properties (SMECK & CIOLKOSZ, 1989). Other features, such as low hydraulic conductivity (FRANZMEIER & *alii*, 1989) and total porosity, generally < 35% (WITTY & KNOX, 1989) have been recognised as distinctive.

Fragipan micromorphology reveals some common features: clay-bridges between grains (LINDBO & VENEMAN, 1989), a stipple speckled b-fabric associated with compound coatings or infillings of clay and fine silt laminations (MC INTOSH & KEMP, 1991). In some cases, appear highly developed complex cutans, sometime partially destroyed and incorporated into the matrix (BARONI & CREMASCHI, 1987).

In spite of many studies, the current definition of a fragipan in Soil Taxonomy (SOIL SURVEY STAFF, 1992) has proved to be inadequate for consistent identification (WITTY & KNOX, 1989). Recently, suggestions have been made that there is a need to develop better criteria to separate true fragipan from materials that exhibit fragic character, as dense basal tills, or «degraded» fragipan (SMECK & CIOLKOSZ, 1989). The term «soils with consolidated horizons», referring to high bulk density (more than 1.6 $Mg.m^{-3}$) of the soil matrix, has been proposed to encompass soils that differs in morphology and classification, but are similar for limiting root and water penetration (MC INTOSH & KEMP, 1991).

In Italy, fragipan has been found in the central and western Po river valley on glacial and fluvioglacial terraces (ARDUINO & *alii*, 1982, CREMASCHI, 1987, PREVITALI, 1985, AJMONE-MARSAN & *alii*, 1994). The soils, showing fragic properties ranging from 30 to 100% of the horizon, have been classified in Fragic great group (ERSAL, 1988). Although fragipans in non-glaciated Mediterranean environment have not yet been reported, the Montagnola Senese area, in central Tuscany, represents a good example of the occurrence of soils showing fragipan and other consolidated horizons in such environment.

The purpose of this study was to investigate both the properties of consolidated horizons in soils evolved from mainly siliceous colluvial and alluvial deposits in a Mediterranean environment and the relationships between the occurrence of these horizons and the geomorphological evolution of the area during the Quaternary.

2. MATERIALS AND METHODS

2.1 *Main geographical and geological features*

The area known as «Montagnola Senese» is located in Central Tuscany and it extends over almost 20 km². It is constituted of several hills with an average height ranging from 400 and 500 and a maximum of 671 meters a.s.l.

Four lithological units could be distinguished: (1) acid metamorphic rocks, consisting of chloritic and sericitic fine-grained schist, jasper, quartzose micro and macro conglomerate and violet schist breccias (Mesozoic); (2) calcareous material, composed of flint limestone, marble, dolomite and cavernous limestone Mesozoic in age, but partially reworked by the Miocene sea; colluvial and alluvial deposits, either (3) mainly calcareous or (4) mainly siliceous of Quaternary age (fig. 6).

2.2 *Climate*

Climatic data for the area have been obtained from Simignano (SI) and Siena. At Simignano (43°18' Lat. N; 419 m a.s.l., 8 km west of Siena) the average annual rainfall is 1019 mm, with maxima in October (119.8 mm) and November (116.6 mm) and minima in July (36.4 mm) and June (46.2 mm). In Siena (43°19' Lat. N; 348 m a.s.l.) the average annual temperature is 13.2°C, the warmest months are July (22.1°) and August (22.0°); the coldest are January (5.8°) and December (6.3°). The annual Potential Evapotraspiration of Thornthwaite is estimated at 735 mm; total annual deficit ranges from 97 to 185 mm and surplus from 380 to 469 mm for soils with Available Water Capacities from 200 to 50 mm. The soil moisture regime, evaluated by the Newhall Computation (NEWHALL, 1972) is «udic» with a water holding capacity of 200, 100 and 50 mm, whereas the soil temperature regime, according to Soil Taxonomy (SOIL SURVEY STAFF, 1992) is «mesic» ($8<T<15°$ C).

2.3 *Vegetation*

The Montagnola Senese is mainly a forested area. Historical research documented that the forest cover was

FIG. 1 - Some soils of the Montagnola Senese area have a subsurface close-packed horizon matching the diagnostic criteria of a true fragipan.

FIG. 2 - In soils where fragipan or densipan is placed near the surface, degradation occurs, as manifested by glossic features.

FIG. 3 - Densipans are very thick horizons, like to fragipan but lack of bleached streaks and structure; they can be found in karst depression and in ancient colluvial areas, far from the soil surface, unless truncated by erosion.

FIG. 4 - Close-packed horizons classified as pedal dense subsurface horizons are not brittle and the bleached streaks are not coarser than the matrix. They show different types of prismatic or angular blocky structure.

FIG. 5 - Arable land and the buildings mark the terraced alluvial fan of Pievescola, while the relieves of the Montagnola Senese rise in the background.

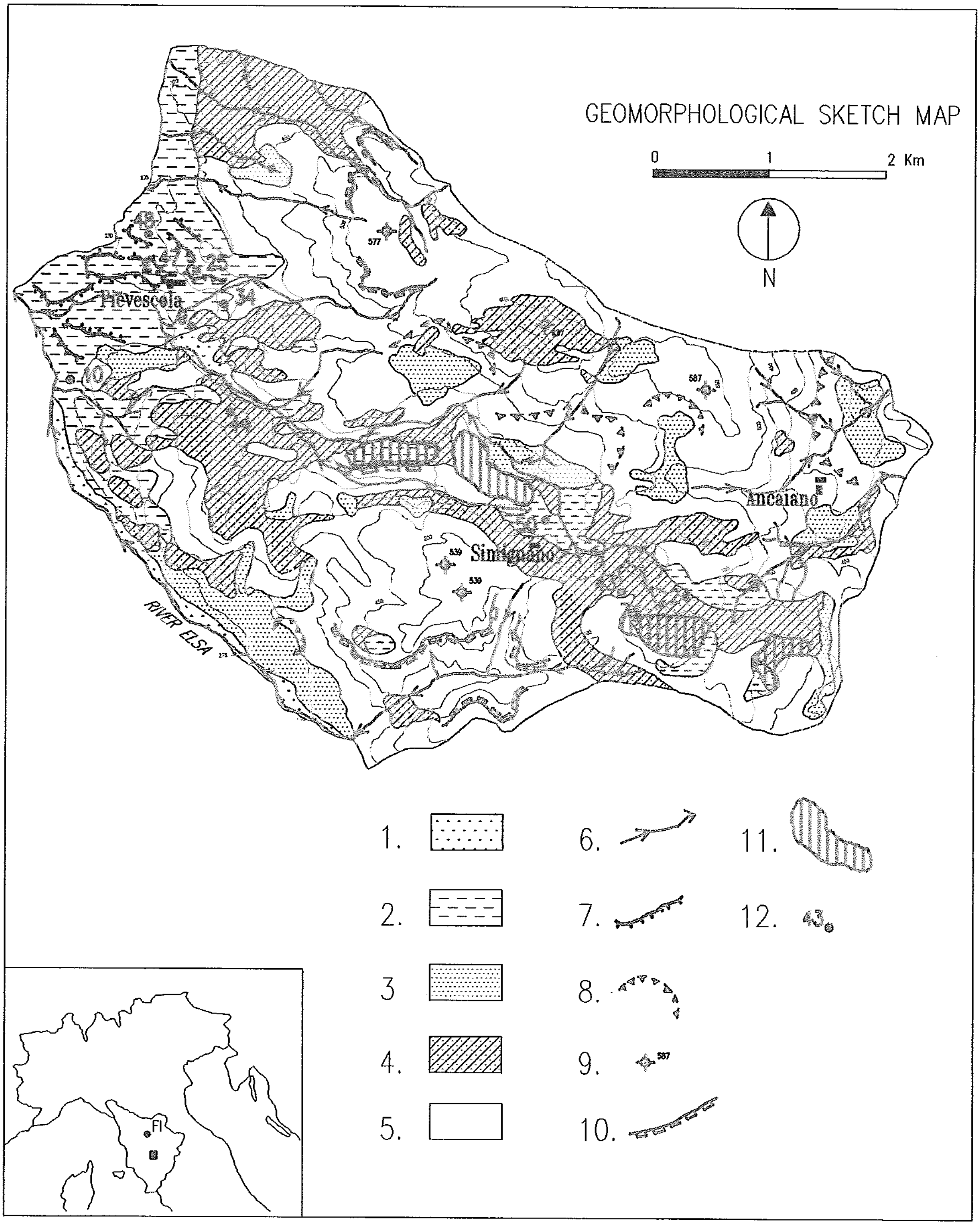


Fig. 6 - Geomorphological sketch map of the study area. Legend: 1) recent alluvial deposits; 2) mainly clayey-siliceous alluvial deposits; 3) mainly calcareous colluvial deposits; 4) marl, clay and siliceous schists, jaspers, quartzose conglomerates and violet schist breccias; 5) flint limestones, marbles, dolomite and cavernous limestone breccias; 6) stream; 7) terrace edge; 8) karst depression edge; 9) rounded summit with heigt (a.s.l.); 10) lithological or structural scarp; 11) structural surface; 12) profile.

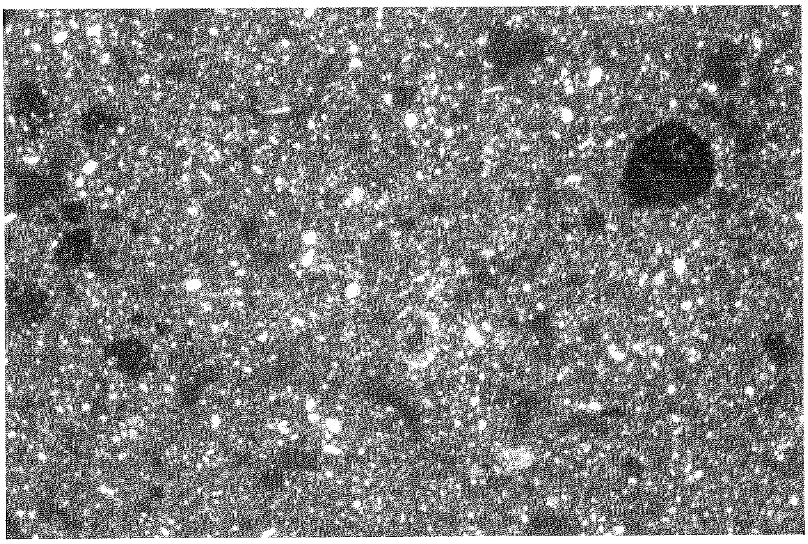


FIG. 7 - Apedal mass of a fragipan with FeMn nodules: pores are not interconnected and the coarse fraction is moderately sorted. X.P.L. 40x.

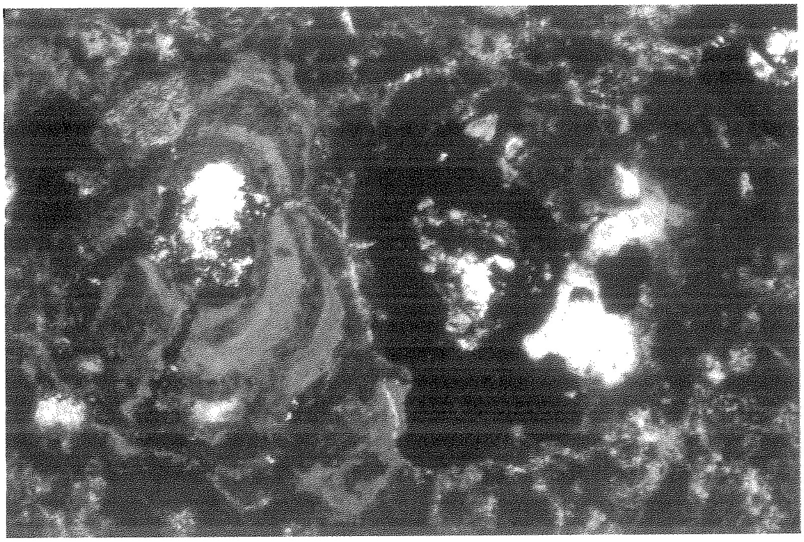


FIG. 8 - Red clay coating alternating with silt in a close-packed horizon. X.P.L. 80x.

continuous since the Roman age (REDON, 1989), and probably since the beginning of the Holocene, preventing wind erosion and large denudative phenomena. Arable land is limited to the bottom of the largest dolines and the colluvial footslopes (fig. 5).

Different forests predominate depending on the nature of rock and sediments, as well as soil on the moisture available. The most important governing factor for forest distribution is the soil reaction: on acid rock and soil chestnut tree (*Castanea sativa*) dominates, while on carbonatic substrate the vegetation is marked by the presence of the evergreen holm oak (*Quercus ilex*), often associated with turkish oak (*Quercus cerris*) and other deciduous broadleaf species.

2.4 Soil and terrain analysis

Terrain analysis and geomorphological map were performed following the Italian National methodology (PELLEGRINI & *alii*, 1993) and the International Institute for Aerial Survey and Earth Sciences system (I.T.C., 1978). The soil survey led to the description and routine analysis of 50 profiles in all, among them 11 were chosen to perform specialistic analysis. Soils were described and classified according to the Soil Survey Manual (SOIL CONSERVATION SERVICE, 1990), Soil Taxonomy (SOIL SURVEY STAFF, 1992) and FAO-UNESCO (1988). In the laboratory, routine analyses were performed according to S.I.S.S. (1985). Cation exchange capacity and exchangeable bases by NH_4OAc. extraction and spectroscopy; cation exchange capacity of the clay fraction was measured on samples of clay separated by sedimentation. Gasometric determination of $CaCO_3$ was performed on all but the acid horizons. Total iron was determined on dissolution extracts obtained by acid attack with a mixture of HCl: HNO_3: HF. Oxalate-soluble iron was estimated after SCHWERTMANN's method (1964). DCB-extractable iron and silica were determined after MEHRA & JACKSON (1969). Plinthite nodules were submitted to the WOOD & PERKINS test (1976), with immersion of specimens for two hours in water, to check the persistence of aggregation. Iron content of rock was determined after acidic digestion (JACKSON, 1958).

Undisturbed soil cores were sampled in triplicate to determine physical and hydrological characteristics. Hydraulic conductivity was determined by the falling-head method and bulk density by the core method (HALL & *alii*, 1974). Hydraulic conductivity classes were established according to KLUTE & DIRKSEN (1986). Air dried aggregates, 0.5-1.0 cm^3 in volume, were outgassed and intruded with mercury using a Carlo Erba 200 porosimeter equipped with a Carlo Erba 120 macropore unit. Pore size distribution curves were calculated in the range 200-0.007 μm equivalent cylindrical diameter with the Young-Laplace equation, assuming cylindrical pores, a surface tension of mercury of 480 $dynes.cm^{-1}$ and a contact angle of mercury on soil of 141°. Total porosity was measured from bulk density, assuming a particle density of 2.65 $Mg.m^{-3}$ (HALL & *alii*, 1974). Three pore classes (>50, 50-0.5, <0.5 μ, GREENLAND, 1977) were calculated from total porosity and from mercury porosimetry data.

The micromorphological investigation was conducted on replicated samples of 24 horizons belonging to 16 profiles, for 42 (mostly 80x50 mm) thin sections in all, following the methodology developed by BULLOCK & *alii* (1985).

2.5 Identification of close-packed horizons

The pedological and geomorphological survey of the central part of the Montagnola Senese led to individuate several soils with close-packed horizons differed for morphology and position on the landscape, but all distributed only on siliceous deposits.

The term «close-packed» was chosen to indicate horizons with low air capacity and high packing density (packing density = bulk density + 0.009*clay, THOMASSON, 1992), specifically higher than 1.90. Besides high density, these horizons, in spite showing different morphologies, appeared to be similar for limiting root and water penetration as well as for parent material.

Close-packed horizons were then classed into four main types:

1) true fragipan, matching the following field diagnostic criteria (WITTY & KNOX, 1989): a) brittleness of the matrix at or near field capacity throughout the subhorizons, or at least in any large prismatic structural units that have horizontal dimension of 10 cm or more and constitute 60% or more of the volume, b) slaking in water of air-dry fragments 5 to 10 cm in size, c) virtual absence of roots except in vertical streaks between any large prismatic structural units, d) evidence of pedogenesis in the forms of mottles and clay films, e) presence of common vertical bleached streaks defining very coarse prisms and describing a polygonal pattern on a horizontal exposure, with a texture coarser than the matrix (fig. 1).

2) Glossic close-packed horizon: following the definition proposed for «degraded fragipan» by HUNDALL & WILLIAMS (1989), horizon in which fragic material does not meet the volume requirements of the fragipan horizon. As a rule, this layer shows many bleached streaks and tongues forming a «glossic» horizon (SOIL SURVEY STAFF, 1992) (fig. 2).

3) Densipan: close-packed horizon similar to fragipan except for the bleached streaks, that are rare; the structure ranges from moderate coarse prismatic to massive (fig. 3).

4) Pedal dense subsurface horizon: close-packed horizon that is not brittle and whose bleached streaks are not coarser than the matrix, with different types of prismatic or angular blocky structure (fig. 4).

The first and the last typologies could be further subdivided into two sub-types regarding the colour, the texture and occurrence of plinthite.

Relationships between the close-packed horizons were also considered, because same profiles could have dissimilar typologies inside. In particular, glossic close-packed horizon was always found over fragipan or densipan, near the soil surface, where the most part of the root development took place. Unless truncated by erosion, fragipan and densipan were underlying either glossic horizons or colluvial deposits; when found in the same profile, fragipan was always upon densipan.

Close-packed horizons were found in many soils on gentle

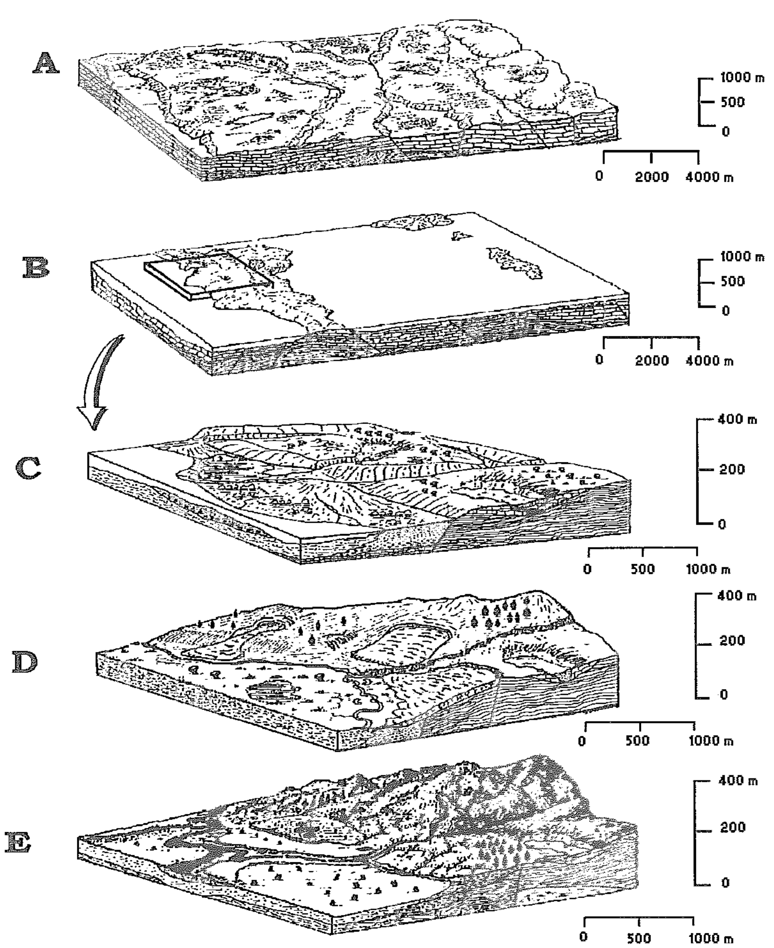


FIG. 9 - Geomorphological evolution scheme of the Montagnola Senese (partially taken from GIANNINI & LAZZAROTTO, 1970): A - during late Miocene the whole Montagnola must have looked like a plateau affected by fluvio-lacustrine processes and karstification of the calcareous rocks; B - during early and middle Pliocene the area consisted of a low ridge made of small hills; C - the strong uplifting occurred during late Pliocene caused strong slopes erosion and formation of large coalescent fans along main faults; D - after the relatively stable early Pleistocene, the middle and late Pleistocene were characterised by alternate uplifting and by climatic changes related to glacial phases. During cold and humid periods, slope erosion led to the formation of extensive and thick colluvial deposits on all the stable surfaces. The tectonic tilting produced a rapid lowering of the water-tables, and the consequent dissection of colluvial deposits, with the formation of the close-packed horizons; E - during the Holocene, tectonic step-rising remained active, however the forest cover and climate characteristics caused linear erosion processes, with dominance of rills and gullies.

slopes and relatively stable surfaces, or from slopes that were stable before being tilted and displaced by tectonic movements. Profile 7, having a glossic horizon on a densipan, is an example of soil developed on slope sediments, formed mainly from schist and quartzite, in a karst depression developed on a structural surface (table 1). Profile 9, characterised by a glossic horizon on a fragipan, is situated near the apex of a fan, where thin colluvial deposits cover alluvial materials and strongly weathered schist (saprolite). Profile 48 is representative of the soils formed in the terraced alluvial fans bordering the slopes near Pievescola, in particular of those having a pedal subsurface horizon with plinthite.

3. RESULTS

3.1 Geomorphological evolution

The sequence of geomorphological processes occurred in the study area was established by a semi-detailed geomorphological survey (fig. 6) and from the information about the local and regional geology reported by GIANNINI & LAZZAROTTO (1970) and BARTOLINI & *alii* (1982).

The geomorphological evolution of the Montagnola Senese started from the late Miocene onward, when orogenic activity on a regional scale had stopped. The whole area must have appeared as a plateau affected by fluvio-lacustrine processes and karstification of the calcareous rocks (sketch A in fig. 9). During the early and middle Pliocene, following the sea transgression, the Montagnola was a low ridge made of little hills that divided two different marine basins (sketch B). The late Pliocene was characterised by a general strong uplifting of all Tuscany and by sea regression. These tectonic processes are particularly evident in the Montagnola Senese (BARTOLINI & *alii*, 1982). They triggered a strong slope erosion, with formations of a series of coalescent alluvial fans at their bottom, at the mouth of principal valleys, and colluvial deposits into karst depressions (fig. 6). In the case of alluvial fans bordering the slopes of the western ridge, the material washed down from slopes was of a quite coarse particle size, pointing to transport and deposition in a rather high energy environment (sketch C). After the relatively stable early Pleistocene, the middle and late Pleistocene were characterised by alternate phases of uplifting and stasis, which in response to climatic changes led to erosion and deposition (BARTOLINI & *alii*, 1982).

Evidence of glacial activity is lacking. During cold and humid erosive events, however, slope erosion was marked

TABLE 1 - Field description and analytical data of soils with different close-packed horizons

Soil with a densipan and a few glosses; profile 7; location: Molli UTM 32TPP771945; 580 m (a.s.l.); land use: grassland with chestnut trees; physiography: structural surface. Classification: Glossic Paleudalf (Soil Taxonomy); Chromi-haplic Luvisol (FAO-UNESCO).

A	0-21 cm; yellowish brown (10YR 5/4), moist; very gravelly silty loam; very friable; weakly fine and medium subangular blocky and strong medium granular structure; common very fine pores; common fine and medium roots; abrupt smooth boundary to:
2Bt	21-50 cm; red (2.5YR 4/6), moist; gravelly clay loam; friable; stronge fine and medium prismatic structure; prominent few fine strong brown (7.5YR 5/8) mottles and coarse pink (7.5YR 8/4) streaks; few fine and very fine manganese nodules; many iron and clay cutans, common manganese cutans; common fine and very fine pores; few fine and medium roots into streaks; diffuse smooth boundary to:
2Btd	50-150 cm; yellowish red (5YR 5/6), moist gravelly clay loam; firm (dense materials >60 % of volume); weakly medium prismatic structure; prominent common fine and medium strong brown (7.5 YR 5/8) mottles and coarse pink (7.5YR 8/4) streaks; common manganese, iron and clay cutans; common fine and very fine and medium roots into the streaks; diffuse smooth boundary to:
2Btd2	150-225 cm; dark reddish brown (5YR 3/4), moist; very gravelly clay loam; firm; massive; prominent common fine and medium strong brown (7.5YR 5/8) mottles and few coarse pink (7.5YR 8/4) streaks; common manganese, iron and clay cutans; common fine and very fine pores; few fine roots into streaks; diffuse smooth boundary to:
2BCd	225-500 cm; dark reddish brown (5YR 3/4), moist; very gravelly clay silt loam; firm; massive; common manganese cutans; few fine and very fine pores; diffuse smooth boundary to:
3BCd	500-700 + cm; dark reddish brown (5YR 3/4), moist; very gravelly clay loam; firm; massive.

Horizon	depth	SAND				SILT	CLAY	pH	Organic	Bulk	Packing
		coarse	medium and fine	very fine	Total	Total	Total		carbon	Density	Density
	cm	(% of the fine earth)						(1:2.5 H_2O)	(%)	(Mg/m3)	(B.D. + 0.009*clay)
A	21	16	12	8	36	55	9	7.5	1.20	1.50	1.58
2Bt	50	7	12	10	29	34	37	6.5	0.30	1.48	1.81
2Btd-o*	150	8	10	10	28	35	37	6.8	0.10	1.66	1.99
2Btd-r**	150	5	13	15	33	44	25	7.2	0.20		
2Btd2	225	7	11	12	30	35	35	6.6		1.64	1.96
2BCd	500	6	6	8	20	41	39	6.4		1.58	1.93
3BCd	700 +	10	11	6	27	38	35	7.2			

* = oxidised mass;
** = reduced streaks.

Soil with a glossic horizon over a fragipan: profile 9; location; Pievescola, UTM 32TPP732972; 270 m (a.s.l.); land use: mixed woodland; physiography: apex of alluvial fan. Classification: Typic Fraglossudalf (Soil Taxonomy); Fragi-chromi haplic Alisol (FAO-UNESCO).

Oi	0-3 cm; black (10YR 2/1), moist; very friable; weakly very fine crumb structure; many very fine, fine and medium pores; abrupt smooth boundary to:
A	3-15 cm; dark yellowish brown (10YR 4/4), moist; gravelly silty loam; very friable; moderate fine and medium granular structure; many fine and very fine pores; many coarse, medium and fine roots; abrupt smooth boundary to:
E	15-45 cm; strong brown (7.5YR 5/6), moist; gravelly silty loam; friable; weakly fine and medium subangualr blocky; many fine and very fine pores; many coarse, medium and fine roots; abrupt smooth boundary to:
Bt	45-110 cm; yellowish red (5YR 5/6), dry; very gravelly silty loam; very hard; strong fine and medium subangular blocky; prominent few iron, manganese and fine pink (7.5YR 8/4) mottles; common fine pores; common fine and medium roots; many iron and clay cutans, common manganese cutans; abrupt wavy boundary to:
Btx	110-115 cm; yellowish red (5YR 5/8), dry; gravelly clay silt loam; very hard (fragic materials <60 % of volume); weakly fine and medium subangular blocky; prominent many coarse pink (7.5YR 8/4) and few fine white (10YR 8/1) streaks with roughly polygonal pattern; few fine pores; few fine and medium roots into the bleached streaks; common manganese cutans, many iron and clay cutans; abrupt wavy boundary to:
2Btx	155-217 cm; yellowish red (5YR 5/8), dry; sightly gravelly clay loam; very hard; massive, prominent many coarse, medium and fine white (10YR 8/1) and pink (7.5YR 8/4) streaks with roughly polygonal pattern; common iron and clay cutans; abrupt smooth boundary to:

3Bt 217-264 cm; yellowish red (5YR 5/8), dry; very gravelly clay loam; very hard; massive; prominent few fine yellowish red (5YR 5/6) and medium pink (7.5YR 8/4) mottles; many iron, manganese and clay cutans; abrupt wavy boundary to:

4CB 264-280 + cm; yellowish red (5YR 5/8), moist; gravelly loam; firm; massive.

Horizon	depth	SAND coarse e	 medium and fine	 very fine	Total	SILT Total	CLAY Total	pH	Organic carbon	Bulk Density	Packing Density (B.D. + 0.009*clay)
	cm	(% of the fine earth)						(1:2.5 H_2O)	(%)	(Mg/m3)	
A	15	21	10	5	36	53	11	6.7	2.10	1.23	1.33
E	45	12	7	6	25	58	17	4.9	0.80	1.56	1.71
Bt	110	11	7	5	23	52	25	4.6	0.20	1.44	1.66
2Btx1	155	8	5	6	19	51	32	5.2	0.31	1.68	1.97
2Btx2-o	217	9	6	6	21	46	33	5.4		1.63	1.93
2Btx2-r	217	6	7	6	19	67	14	4.8			
3Bt	264	14	8	6	28	44	28	5.0			
4CB	280 +	12	9	6	27	51	22	5.9			

Soil with pedal dense subsurface horizons: profile 48; location: Pievescola, UTM 32TPP729979; 272 m (a.s.l.); land use: grassland; physiography: terraced alluvial fan. Classification: Plinthaquic Paleudalf (Soil Taxonomy); Plinthi-stagnic Luvisol (FAO-UNESCO).

Ap 0-40 cm; yellowish brown 10YR 5/4, moist; sligthly gravelly clay loam; friable; weakly fine and medium subangualr blocky; fine and coarse common pores; fine and medium common roots; worm borrows; abrupt smooth boundary to:

Bt 40-50/55 cm; brownish yellow 10YR 6/6, moist; slightly gravelly silty clay; firm; moderate fine subangular blocky within prismatic structure; prominent many medium reddish yellow (5YR 6/8), common medium light gray (5YR 7/1) and coarse red (2.5YR 4.5/7) mottles; common iron and clay cutans; very few medium and coarse iron concrections; very fine few pores; fine and medium few roots; clear smooth boundary to:

2Btg 50/55-78 cm; yellowish red (5YR 5/6), moist; slightly gravelly silty clay; firm; moderate medium prismatic structure; prominent many coarse light gray (5YR 7/1) and common medium red (10R 4/8) mottles; few medium and coarse iron concretions; common iron and clay cutans; few very fine pores; gradual smooth boundary to:

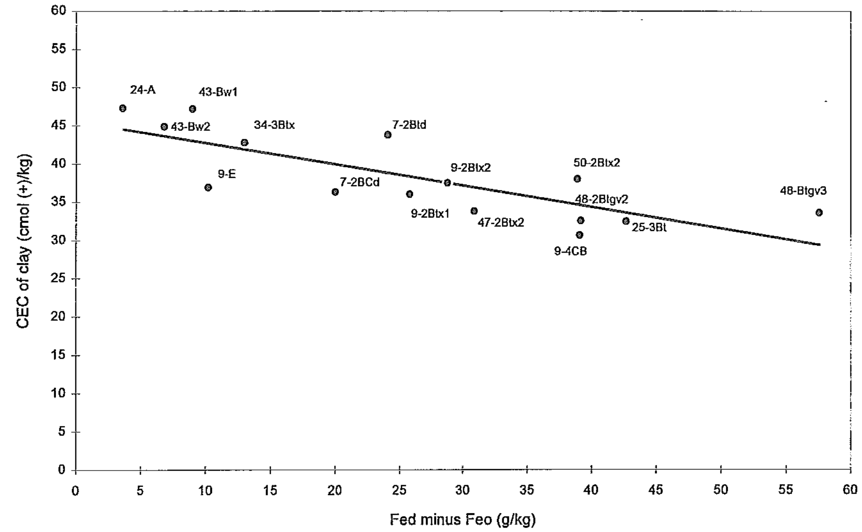
2Btgv1 78-190 cm; strong brown (7.5YR 5/8), moist; gravelly clay loam; very firm; moderate coarse and medium prismatic structure; prominent many coarse light gray (5YR 7/1) and medium reddish yellow (5YR 6/8) mottles; common medium and coarse plinthite fragments constituted by iron concentrations; common iron and clay cutans; few very fine pore; diffuse smooth boundary to:

2Btgv2 190-210/220 cm; reddish yellow (7.5YR 6/8), moist; slightly gravelly clay loam; very firm; massive; prominent many coarse ligth gray (5YR 7/1) and few medium reddish yellow (5YR 6/8) mottles; common medium and coarse plinthite fragments constituted by iron concentrations; few iron and clay cutans; few very fine pores; clear smooth boundary to:

3Btgv3 210/220-310/330 + cm; ligth gray (5YR 7/1), moist; extremely medium gravelly sandy loam; very firm; massive; prominent many coarse and reddish yellow (7.5YR 6/8) mottles; many medium and coarse dark red (10R 3/6) plinthite fragments constituted by iron concentrations; few iron and clay cutans.

Horizon	depth	SAND coarse	 medium and fine	 very fine	Total	SILT Total	CLAY Total	pH	Organic carbon	Bulk Density	Packing Density (B.D. + 0.009*clay)
	cm	(% of the fine earth)						(1:2.5 H_2O)	(%)	(Mg/m3)	
Ap	40	8	8	7	23	41	36	6.4	1.30	1.63	1.95
Bt	55	3	3	4	10	39	49	5.2	0.60	1.51	1.95
2Btg	78	2	4	4	10	42	48	5.4	0.50	1.62	2.05
2Btgv1-o	190	4	10	9	23	42	35	7.3	0.50		
2Btgv1-r	190	2	4	7	13	47	40	6.9	0.40		
2Btgv2-o	220	3	10	13	26	43	31	8.2	0.04		
2Btgv2-r	220	1	5	9	15	44	41	7.6	0.40		
3Btgv3-o	310 +	30	21	7	58	26	16	8.1	0.05		
3Btgv3-r	310 +	12	16	8	36	29	35	7.9	0.01		

FIG. 10 - Relationship between crystalline iron oxides (Fe_d *minus* Fe_o) and CEC of clay for some selected horizons ($y = 45.5 - 0.28x$; $r^2 = 0.623$; $P<0.01$).



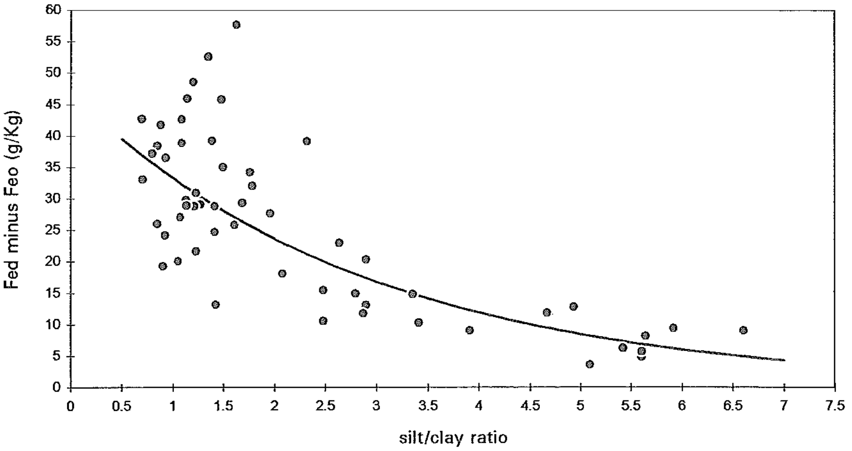
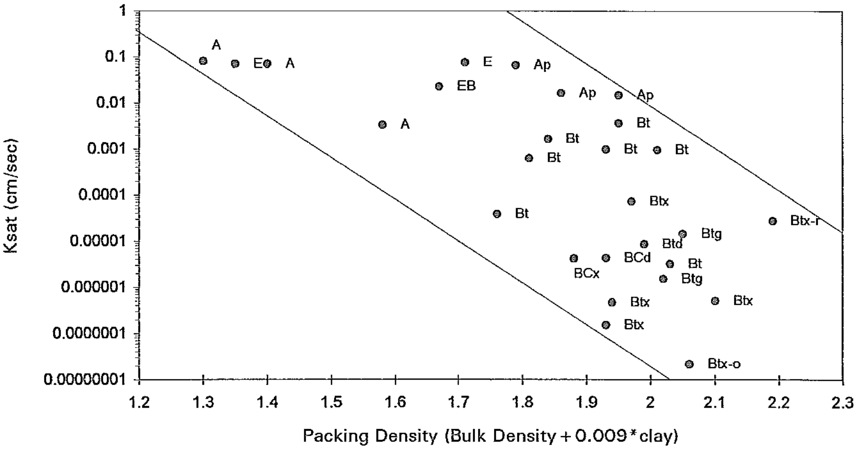


FIG. 11 - Relationship between silt/clay ratio and crystalline iron oxides (Fe_d *minus* Fe_o) ($y = 46.8 * 0.71^X$; $r^2 = 0.717$; $P<0.01$).

FIG. 12 - Relationship between packing density and hydraulic conductivity (in log scale) for selected soil horizons.



by colluviation and mass movements. These events caused the formation of extensive and thick colluvial deposits on all the stable surfaces, while during the cold and dry stages wind erosion occurred (COSTANTINI & *alii* 1992; MIRABELLA & *alii*, 1992). The tectonic tilting produced a rapid lowering of the water-tables, and the consequent dissection of colluvial and alluvial deposits (sketch D).

During the Holocene, the Montagnola Senese area had almost reached its current morphological configuration: tectonic uplifting continued, but because of the forest

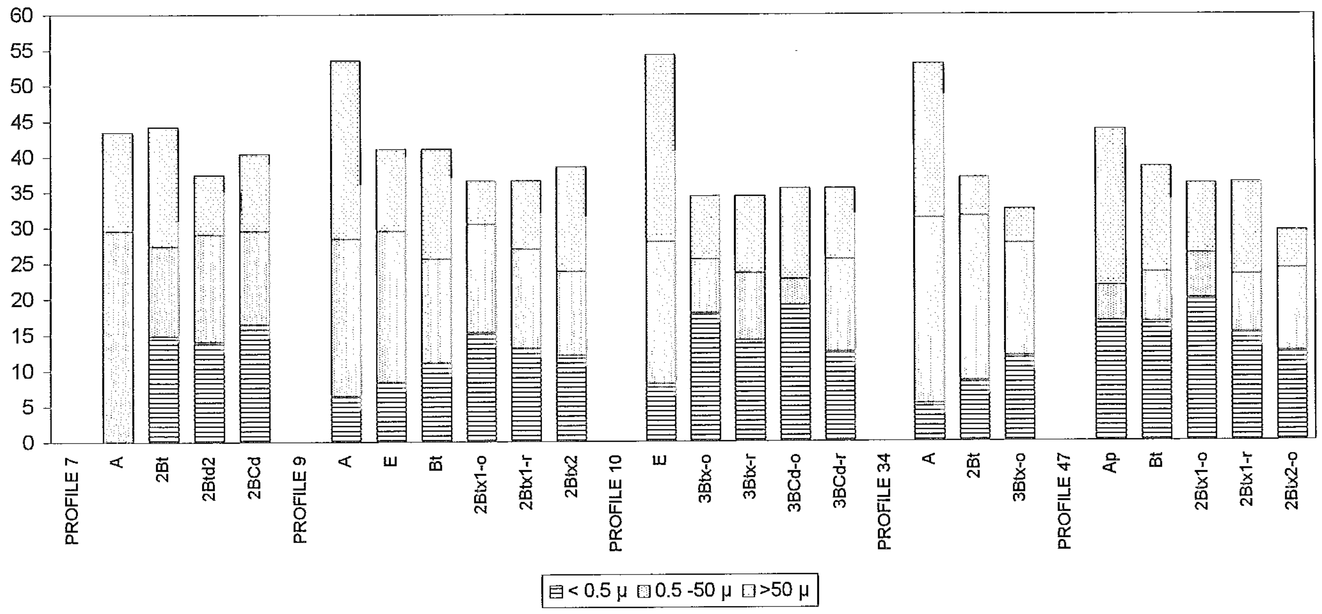


FIG. 13 - Porosity of selected profiles with close-packed horizons (% of volume).

cover and climatic conditions, only linear erosion occurred, mainly in the form of rills and gullies (sketch E). Old surfaces were masked by accumulations of new deposits, or partially destroyed, exposing the upper part of ancient deposits.

In all the depressed areas, the water-table lowered: nowadays it persists in the proximity of the Elsa river at a depth of four to eight meters from the surface.

3.2 Soil classification and age

As mentioned above, the area underwent intense geomorphological evolution during the Pliocene and Quaternary, with alternating periods of erosion and stability. The rising of the Montagnola Senese led to the erosion of slopes, but several surfaces remained stable (e.g. karst depressions) or were stable for a long time (e.g. colluvial areas). Because of stable and unstable surfaces, soils on this landscape differ for degree of evolution and age. According to the Soil Taxonomy (SOIL SURVEY STAFF, 1992) soils were classified as Udorthents, Dystrochrepts, Hapludalf, Fragiudalf, Fraglossudalf and Paleudalf, or as Dystric Leptosols and Cambisols, Haplic, Stagnic and Chromic Luvisols, Haplic and Ferric Alisols according to the FAO-UNESCO system (FAO-UNESCO, 1988). The various taxa correspond to soils different in age and iron content (fig. 14).

The upper part of the profiles, especially under forest, showed acidification and a decrease in CEC of clay of mineral layers (E horizons), as found by VAN WESEMAEL (1992) in similar conditions, but also clay leaching (see for example table 1, profile 9). Subsurface Bt horizons were found even in soils on steep slopes, but the most evolved ones showed few traces of clay illuviation, while iron accumulation became dominant (profile 48).

Some chemical parameters, crystalline iron oxides (Fe_d *minus* Fe_o) content, silt/clay ratio and CEC of clay, were the chosen parameters to establish the relative degree of evolution between soils. The general evolutive trend proved to be correlated with a progressive increase of extractable crystalline iron content and a slight reduction of the CEC of clay (fig. 10), as well as a decrease in the silt/clay ratio (fig. 11).

Regarding soil age, the only available dating is from the bottom of profile 7, ascertained to be at least Cromerian (Lower-Middle Pleistocene, PANIZZA, 1985) by means of paleonthological finds (FONDI, 1972). However, on the basis of geomorphological reconstruction, micromorphological evidences and chemical characteristics, it is possible to assess the approximate age of the selected soils dating back to Holocene, Upper and Middle Pleistocene, and to Lower Pleistocene ages (fig. 14). Micromorphological results, in particular, concur with those found by CREMASCHI & SEVINK (1987) in Italy in soils belonging to the same Pleistocene ages.

3.3 Properties of close-packed horizons

All the close-packed horizons proved to be similar as far as limiting root and water penetration. Close-packed horizons did not show significant bulk density differences among the different typologies, while both bulk and pack-

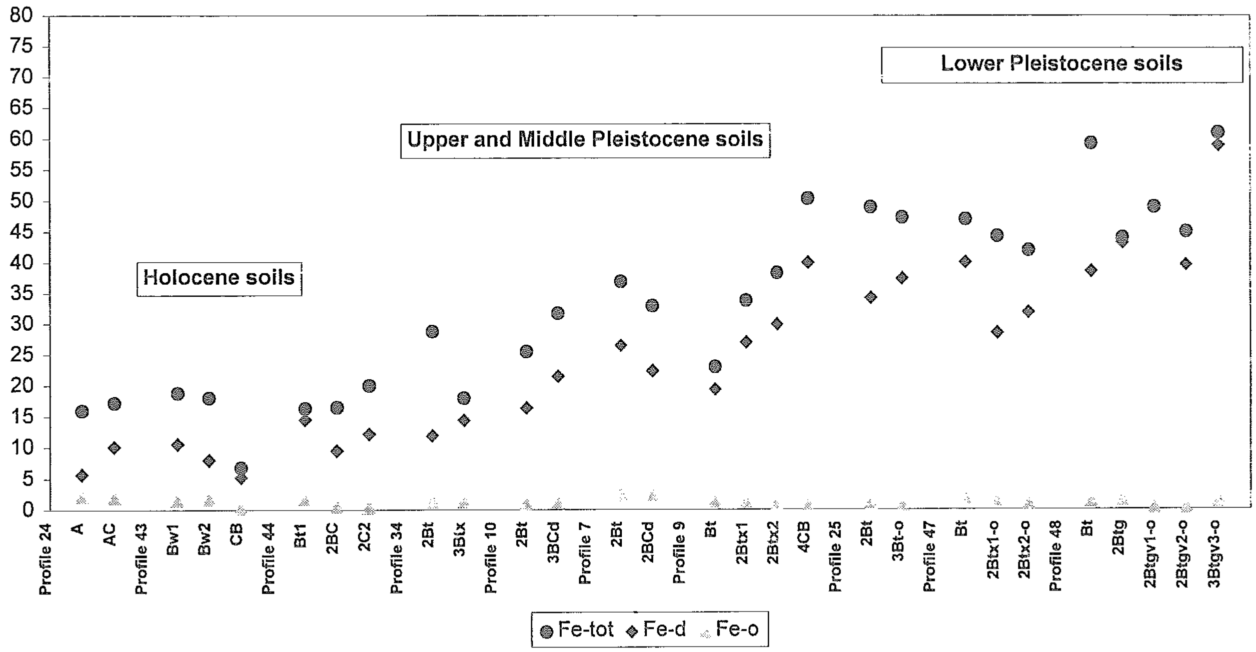


FIG. 14 - Iron forms (Fe-total, Fe-dithionite, Fe-oxalate) of selected profiles according to their estimated age (Fe_2O_3 (g.Kg-1).

ing density were inversely correlated with hydraulic conductivity. The relationship was significant: $r^2 = 0.648$ and $r^2 = 0.610$ with $P<0.01$ for packing and bulk density respectively.

The relationship between packing density and hydraulic conductivity is described in figure 10; the logarithmic scale of K_{sat} shows the great difference in conductivity between surface and subsurface horizons. In particular, K_{sat} of the matrix in the close-packed horizon was always lower than 10^{-4} cm.s^{-1}, but in most cases lower than 10^{-5} or 10^{-6} cm.s^{-1}.

Some considerable differences among the close-packed horizons were found in terms of particle size. Texture of the fine-earth fraction of fragipan and glossic horizons was in most cases silt loam or silty clay loam, with a percentage of clay generally lower than 35; only the reddest ones could be more clayey. On the other hand, densipans and pedal dense subsurface horizons usually had more than 35% of clay in the fine earth fraction. As a rule, all close-packed horizons had a texture dominated by silt, with a small amount of coarser than very fine sand, when the clay percentage could be more variable, according to typology.

Another characteristic textural distinction among close-packed horizons was related to the reduced zones: fragipans, glossic horizons and densipans had bleached streaks coarser than the oxidised matrix, while they were equal or finer in pedal dense subsurface horizons.

Porosity was measured in selected horizons of 5 profiles, and distinguished into three classes: macro, meso and micropores (>50 μ, 0.5-50 μ, <0.5 μ, respectively, GREENLAND, 1977), as shown in figure 11. Horizons were then grouped in: surface (horizons A, Ap and E) and argillic horizons (horizons Bt), densipans (horizons Btd and BCd-o) and fragipans (horizons Btx-o). Their porosity classes were submitted to analysis of variance (ANOVA) (tab. 2). The most important differences were noticed between surface horizons and all the others. Nevertheless, fragipan and densipan proved to be dominated by the micro and mesoporosity: the macro/micro porosity ratio ranged from 2.6 in surface horizons, to 1.0 in argillic, 0.64 in densipans, to 0.55 in fragipans.

Porosity of oxidised mass and reduced streaks in fragipans and densipans were also analysed (fig. 13). Results indicated the two horizon parts did not differ significantly for total porosity, but did in microporosity, which was always higher in the mass than in the bleached streaks.

With reference to chemical characteristics, all horizons were free of $CaCO_3$ but base saturation strongly ranged between soils and horizons. Values increased from soils on steep slopes to those on gentle slopes and on the fans, following the morphological position and the influence of nearby limestone formations. Cation exchange capacity generally was rather low, with variations correlated with organic matter, clay content and activity. Silica and Fe_2O_3 dithionite contents of close-packed horizons did not correlate with bulk or packing density or with hydraulic conductivity. The mean SiO_2d in 13 close-packed howas 1.44 ± 0.165 g.Kg^{-1}, which is lower than the 2 g.Kg^{-1} threshold suggested by some Authors for fragipan (HARLAND & *alii*, 1977). Firm horizons did not show important differences for SiO_2 or in Fe_2O_3 content; but iron forms did differ among soils, both in terms of total iron and Fe_2O_3d, according to the estimated age (fig. 14).

TABLE 2 - Micro, meso, macro and total porosity (% of vol.) of different horizons (oxidised matrix) belonging to soils with close-packed layers

	HORIZON TYPOLOGY			
	surface (hor.: A, Ap, E)	argillic (hor.: Bt)	densipan (hor.: Btd, BCd)	fragipan (hor: Btx)
microporosity (<0.5 μ)	7.5 Cˆ	12.8 B	16.5 A	15.0 A
mesoporosity (0.5 - 50 μ)	20.6 A	14.3 B	10.5 C	11.3 C
macroporosity (>50 μ)	19.7 A	13.1 B	10.7 BC	8.3 C
total porosity	47.8 A	40.2 B	37.7 B	34.6 B

ˆ Means in the same row and with the same letter are not significantly different (Student-Newman-Keuls test with $P < 0.05$). ANOVA: microporosity $F = 16.79$ ***, mesoporosity $F = 8.76$ ***, macroporosity $F = 19.78$ ***, total porosity $F = 11.4$ **.

3.5 Micromorphological characteristics of close-packed horizons

3.5.1 Description

Preserved fragipans and densipans were apedal, while glossic horizons and pedal dense subsurface horizons could also show strongly developed angular blocky microstructure. Porosity was always lower than 40%, in most cases lower than 30%; in fragipans, densipans and in the mass of the glossic horizons, pores were not interconnected (fig. 7).

The coarse/fine (c/f) ratio at 10 μ were, as a rule, 1:1 in fragipans, densipans and glossic horizons, but 2:3 in the redder fragipans and in the pedal dense subsurface horizons. Sorting of silt in the coarse fraction was a common feature in fragipans, glossic horizons and densipans, as well as unsorting in the pedal dense subsurface horizons.

Composition of all soils appeared to be very similar: quartz, polycrystalline quartz, quartzite, schist fragments, plagioclases (mainly albite) and muscovite were, in order of abundance, the most common minerals; only in the horizons where the coarse fraction was more altered did the presence of schist fragments decreased, while muscovite and albite increased.

Schist fragments and the quartzites resulted the largest minerals, rounded and elongated in shape, with random distribution pattern. Moreover, they were particularly affected by the alteration, from which a large amount of silt appeared to be originated. As a whole, the degree of mineral alteration varied quite widely between close-packed horizons: the less weathered horizons could show moderate alteration of schist fragments and quartzites, but plinthic horizons could exhibit up to moderate alteration of quartz and polycrystalline quartz.

The fine fraction usually appeared as speckled clay and silt with amorphous FeMn oxides, with colour ranging from strong brown to red according to the iron concentration.

Very few organic components like tissue fragments, root remnants and living roots were present in the bleached streaks of densipans, fragipans and glossic horizons.

As to the groundmass, the c/f distribution was always porphyric, whereas the birefringent fabric (b-fabric) was undifferentiated or weakly stipple-speckled in all the close-packed horizons, but it was striated or reticulated in the reduced patches of the pedal dense subsurface horizons.

Among the textural pedofeatures, dusty and compound clay coatings and infillings, also forming bridges between pores, were present in all the firm horizons, but their frequency could not be related to packing density. Their colour was orange, red or yellow; orange and yellow ones more frequent within the depletion zones. Clay coatings often appeared deformed, disrupted and sometimes embedded into the matrix. In profiles developed on the terraced alluvial fans near Pievescola, clay coatings and infillings were red and orange in the oxidised mottles, but yellow or white, because completely deferrified, in the reduced ones. Leptocoatings (CREUTZBERG & SOMBROEK, 1987) were also observed around aggregates of plinthic soils. As a rule, these last soils had much lesser clay coatings than the others.

Silt and fine sand infillings and coatings were present in all the close-packed horizons, but also in this case their frequency appeared to be not proportional to packing density. These pedofeatures habitually cover or alternate with clay coatings, or have fragments of clay coatings and FeMn hypocoatings inside; they showed the same colour of the matrix or had a brighter one, like that of the depletion zones (fig. 8).

Redox depletion zones always occurred along planes. They were mega yellowish brown hypocoatings, with the same grain arrangement than the matrix, or silt and fine sand coatings (clay depletions or «skeletans»), but they appeared as mega white and yellowish brown hypocoatings in the pedal dense subsurface horizons.

Redox concentrations features were FeMn hypocoatings, also impregnating clay coatings; FeMn masses, pseudomorphes and typic nodules, either with diffuse or sharp boundaries. Skeleton grain inclusions of redox concentrations had the same size, shape, mineralogy and abundance of the host matrix. In depletion zones, nodules showed protruding skeleton grains.

The only prominent fabric pedofeature regarded the coarse fraction, which dominated in the oxidised zones of the plinthic soils, because of nodules formation.

Evidence of frost action, as reported by VAN VLIET-LANOË (1985), was lacking in all the examined samples.

3.5.2 Discussion

A first indication coming from the micromorphological analysis regards the mode of sedimentation of the soil parent material. As testified by the shape and distribution of schist fragments and quartzites, the studied soils appear to be formed mainly from colluvial and alluvial sediments. Thus, sorting of the coarse fraction in fragipans, glossic horizons and densipans call for a relatively low energy environment, whereas unsorting in the pedal dense subsurface horizons of soils near Pievescola fit an alluvial process.

The alteration degree of schist fragments and quartzites is not compatible with a recent transport. This is in good agreement with the hypothesis that the colluviation processes began before the Holocene, and indicate the pre- depositional material was not all already strong weathered before be transported and settled. Moreover, the alimentation basin of all parent materials should have been the same, because mineral composition of all soils is very similar.

The main post-depositional processes pointed out by the investigation can be summarised as follows:

i) weathering of minerals: producing a large amount of silt, clay neoformation and iron releasing;

ii) moving of particles: several generations of relict and recent clay coatings and infillings were detected, especially in not plinthic soils. Furthermore, silt and fine sand infillings were very common. They can be related to the infiltration in soil of water suspended sediments, as a consequence of colluviation processes or draining of saturated soils (Nettleton & *alii*, 1994) and infer environmental conditions characterised by a scarce forest cover (Goldberg & *alii*, 1990). Their colour and particular arrangement testify a great deal of them are old and very old pedofeatures, whose formation should have begun not long after the parent material deposition and continued alternating with clay illuviation.

iii) redox depletion and concentration: the recognised pedofeatures appeared to be «in situ» formed because of relict and actual processes (Vepraskas & *alii*, 1994) and indicate that soils have been affecting for a long time by a seasonal perched water table. Redox depletion always occurred along planes, but only in densipans, fragipans and glossic horizons were associated with skeletans.

iv) structure formation: also in this case densipans, fragipans and glossic horizons showed a different behaviour than pedal dense subsurface horizons. As to the first ones, the formation of coarse aggregates can be related essentially with root penetration, whereas in the last typology the activity of the more clayey groundmass should also have played a role, as evidenced by the striated b-fabric («argillipedoturbation», Bronger & *alii*, 1994).

4. CONCLUSIONS

The different close-packed horizons examined in this study were all found in soils derived from mainly siliceous colluvia and alluvia originated from several depositional events occurred during the Pleistocene. The close-packed horizons manifested evidences of pedogenesis, had high bulk and packing density (the latter higher than 1.90), had very low hydraulic conductivity of the matrix (lower than 10^{-4} cm.s^{-1}) and a porosity dominated by micropores (pores <0.5 µm). They all were free of carbonates and extractable silica did not occur in significant quantities in all the studied horizons.

The recognised four typologies of close-packed horizons (i) fragipan (ii) glossic horizon, (iii) densipan and (iv) pedal dense subsurface horizon, differed in morphology, particle sizes, and sorting of the coarse fraction. The great abundance of silt and very fine sand, derived from the alteration of schist and quartzite in the parent material, was a common characteristic in all densified horizons. Fragipan and glossic horizon had a percentage of clay generally lower than 35, while densipan and pedal dense subsurface horizon could be more clayey.

The origin of the high density of the examined soils can be related to the geomorphological evolution of the surfaces during the Pleistocene and to the lithology of the materials: the step-wise rising of the Montagnola Senese caused the alternating deposition and draining of saturated materials having a high degree of sorting in the fine-earth fraction. Therefore, the «physical ripening» model described by Bryant (1989) for fragipan formation was appropriate to explain the genesis of close-packed horizons in this environment. According to this model, the ramming of sediments occurred in material with a particular range of fine-earth texture. In our case, this texture was present only in those soils developed from siliceous colluvia and alluvia.

From a pedogenetic point of view, pedal dense subsurface horizons of soils near Pievescola differ from the other close-packed for depositional way of parent material and dominant soil processes, which can be referred to the tropical humid climatic conditions of the lower Pleistocene in central Italy (Magaldi, 1979; Bini & Mondini, 1992). On the other hand, fragipan, densipan and glossic horizon can be each other related because expression of distinct stages of a degradation process due to tree roots affecting the rammed soil layers. In this sense, the densipan represents the horizon less influenced by the roots growing, where the pedological weathering developed far from the maximum biological activity zone. The fragipan is a deep horizon in which only few roots can penetrate through the soil mass fractures, to form the characteristic network. The glossic horizon instead is a subsurface horizon where the firm mass is affected by a more intense root activity, which causes the disintegration of the consolidated material. The breaking down process, as well as the formation of bleached streaks, can influence either the coarse prisms of fragipan or the densipan mass, depending on the equilibrium between erosion and deposition achieved on the surface.

The accurate exam of the relationships between glossic close-packed horizons and fragipans or densipans, and between these horizons and the soil surface, can allows the acquisition of useful information about the Quaternary geomorphological evolution of environments where soils with these characteristics are widespread.

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